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Title:

^{3}He Magnetometry for a Neutron EDM Measurement

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^3He Magnetometry for a Neutron EDM Measurement

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Abstract

The behavior of small amounts of polarized ^3He in a bath of superfluid ^4He at temperatures below 1 K is critical to a new technique for measuring the EDM of the neutron. We report on studies to enhance the number of ultracold neutrons produced in such a bath, on the development of neutron tomography in gaseous mixtures, on magnet properties associated with the precession of ^3He, and on preparations for tests of the distribution and diffusion coefficients of ^3He in the bath.

Background and Research Objectives

The search for an electric dipole moment (EDM) of the neutron is of fundamental importance because it has impact on the origin of the observed matter-antimatter asymmetry in the universe and on grand-unified extensions to the standard model (SM) of electroweak interactions. The SM predicts a value for the EDM five orders of magnitude below the current experimental sensitivity. This gap is a window for the discovery of new physics. The great asymmetry in the ratio of matter to antimatter in the universe may be a hint that such new physics is required.

We are developing the technique proposed by Golub and Lamoreaux [1] for making a three order of magnitude improvement in sensitivity at LANSCE. This new technique differs from previous methods by the fact that the ultracold neutrons (UCN) are produced, polarized, and analyzed in a superfluid ^4He bath near 0.5 K. Some of the experimental conditions required to keep errors in the measurement small are 1) that sufficient numbers of UCN are made in the bath, 2) that the external magnetic field for neutron and ^3He precession be uniform to a few parts in a thousand, and 3) that the neutrons and ^3He occupy the same volume. The objective of this research is to investigate aspects of these issues as input to a proposal for DOE funding of the full experiment

Importance to LANL's Science and Technology Base and National R&D Needs

A greatly improved search for the EDM of the neutron is basic nuclear science, a core competency of the Los Alamos National Laboratory.

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Neutron science is an important field at Los Alamos, and such an experiment is often referred to as "the jewel in the program of basic neutron science at LANSCE." A successful experiment would both improve our capabilities for neutron experimentation and gain the laboratory considerable worldwide recognition.

Scientific Approach and Accomplishments

UCN are produced in the apparatus by the scattering of cold neutrons from ^{4}He atoms in the bath. The neutrons loose energy to become UCN while the system gives up heat to the bath. This technique can produce larger densities of UCNs than conventional production methods. The idea, known as superthermal production, was proposed by Golub and Pendlebury [2] in 1972 but only recently experimentally verified [3] in 1999 to be quantitatively correct. Superthermal production rates are proportional to the number of cold neutrons crossing the bath.

We investigated a method to enhance the production rate by trapping the cold neutrons so they traversed the bath several times.[1] The idea is illustrated in Fig. 1. The bath is surrounded by a neutron reflector that causes the neutrons to cross the bath many times. The enhancement is limited by the rate at which neutrons are absorbed by the reflector or escape through the entrance hole. We applied kinetic theory to the system to gain understanding and verified the predicted behavior using a Monte-Carlo simulation to obtain the average path length in the bath. The maximum effect depended on the composition of the reflector and its thickness. The biggest enhancement was a factor of nearly three in 7 cm of beryllium oxide. A factor of 2 could be obtained with 2 cm of polystyrene. Both materials have advantages that should be weighed in the design of the full experiment.

An EDM manifests itself when a strong electric field modifies the precession rate of the neutron in a weak magnetic field. To control systematic errors, it is necessary to have the magnetic field be uniform to a few parts in a thousand over the volume of the bath, in this case planned to be about 10 cm on a side. A coil configuration that is often used to produce a uniform field perpendicular to the axis of a cylinder is the cosθ magnet. [4] The literature does not describe the uniformity of the field when the magnet is contained inside a superconducting magnetic shield. We have performed calculations for the geometry of a bath surrounded by a coil that is contained in a magnetic shield. The calculation solves Poisson's equation under the boundary condition of a superconductor, i.e. the vector potential vanishes at the boundary. The results are that the superconducting shield must have a radius that is 3 cm greater than the coil and that the dimensions of the coil should be 30 cm in diameter by 1.5 m in length.

A real experiment will require penetrations in the superconducting shield. We have found that the penetrations will have to be made of curved superconducting tubes to keep external fields excluded at the required level of a few μG. We continue to study the details of the design.

A key feature of the technique for measuring the EDM is to use ^{3}He as a co-magnetometer to remove systematic errors due to field drifts. To work properly, the ^{3}He must occupy the same location as the neutrons during the measurement. Our major thrust has been to measure the distribution of ^{3}He in a bath of superfluid ^{4}He. The technique we are using is called cold neutron tomography. The idea is to pass a beam of cold neutrons through a test volume that contains some ^{3}He. Some of the neutrons absorb on the ^{3}He. As the total interaction probability is very small, the number of neutrons that absorb is proportional to the path length of the neutron beam through the measurement volume. We are able to detect the reaction because each absorption causes a small amount of light to be emitted in the hard ultraviolet. This light can be converted to a frequency that is detectable with a photomultiplier tube by using a wave length shifter. In our case, we used tetraphenylbutedyene (TPB) evaporated on a piece of highly reflecting aluminized Mylar. A schematic of the arrangement is shown in Fig. 2. As indicated, the Mylar did not sit snuggly against the cell walls, and the shape of the Mylar defined the effective volume.

The neutron beam is highly collimated to a diameter of 0.4 cm. By moving the test cell across this beam, the effective path length is mapped out as a function of the distance transverse to the beam. If the ^{3}He are uniformly distributed, the map of these path lengths will have one shape. If, for example, all the ^{3}He are concentrated along the walls, the result will be quite distinct.

In a gas, the ^{3}He are guaranteed to be uniformly distributed, and the measurements reflect the shape of the Mylar foil. In order to develop the technique, we measured the distribution in a gas for a high concentration of ^{3}He, 0.01. The result is shown in Fig. 3, and the data were taken at neutron flight-path 11a of the Lujan Center at LANSCE. For reference, we have added curves to show the approximate shape of the Mylar and the expectation for a perfect cylinder. The distribution of the data clearly resembles the actual shape of the Mylar much more closely than that of a cylinder. Based on the statistical sensitivity in the gas, we can estimate that the technique will work well down to a concentration of 10^{-7} in a liquid for reasonable counting times. This value is reasonably close to our actual operating conditions.

Superfluid helium is the state of liquid helium below 2.7 K. The temperatures of most interest are near 0.5 K. Reaching such temperatures requires a dilution refrigerator, an item of considerable cost. Fortunately, such a refrigerator existed, and all we needed to do was modify the type of test cell to match it. Even this process is rather involved and requires detailed design and the selection special materials. The new layout has five windows through which the light passes between the test cell and the photomultiplier tubes. These layers are part of the necessary thermal isolation needed to maintain temperatures below 1 K. The glass to metal seal that could withstand the thermal cycling proved to be a challenge. The existing refrigerator was built from stainless steel. We modified our portion to be aluminum to reduce interactions of the neutron beam and the walls. Vacuum tight aluminum to stainless joints with thin walled materials also required special attention.

The dilution refrigerator requires a large array of pumps and cryogenics support. The shielding cave for radiation on flight path 11a was too small to hold this equipment. We redesigned and reconfigured this cave to meet the space requirements of the refrigerator. We made appropriate channels for the refrigerator lines to pass through the shielding wall. We measured the radiation leakage through the penetrations and found it to be within the Los Alamos safety envelope.

All the modified parts of the dilution refrigerator have been received. They have been leak tested after multiple thermal cycles between liquid nitrogen and room temperatures. Both the glass to metal seals and the aluminum to metal joints appear to be reliable. The refrigerator is being reassembled for tests with a radioactive neutron source and for the measurements at the Lujan Center. Unfortunately we could not complete these measurements because the neutron beam has been off for two years at the Lujan center.

Publications

1. Bangert, P., Cooper, M., and Lamoreaux, S., "Enhancement of Superthermal Ultracold Neutron Production by Trapping Cold Neutrons," Nuclear Instruments and Methods, **A410**, 264-272 (1998).

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[1] Golub, R. and Lamoreaux, S., "Neutron Electric-Dipole Moment, Ultracold Neutrons and Polarized ^{3}He," Physics Reports, **237**, 1, (1994).

[2] Golub, R. and Pendlebury, M, Contemporary Physics, 13, 519, (1972).

[3] Doyle, J., Private Communication, (1999).

[4] Walstrom, P., Los Alamos Technical Report LAUR-90-4090.

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Figure 1: A schematic diagram of the apparatus with enhanced superthermal UCN production due to the surrounding neutron reflector.
Figure 2: A schematic diagram of a cylindrical test chamber lined with aluminized Mylar with incident cold neutron coming from the left.
Figure 3: The path length in a gas cell as a measured with neutron tomography as a function of the transverse distance to the beam. The abscissa is in cm and the ordinate is thousand of counts per unit time.

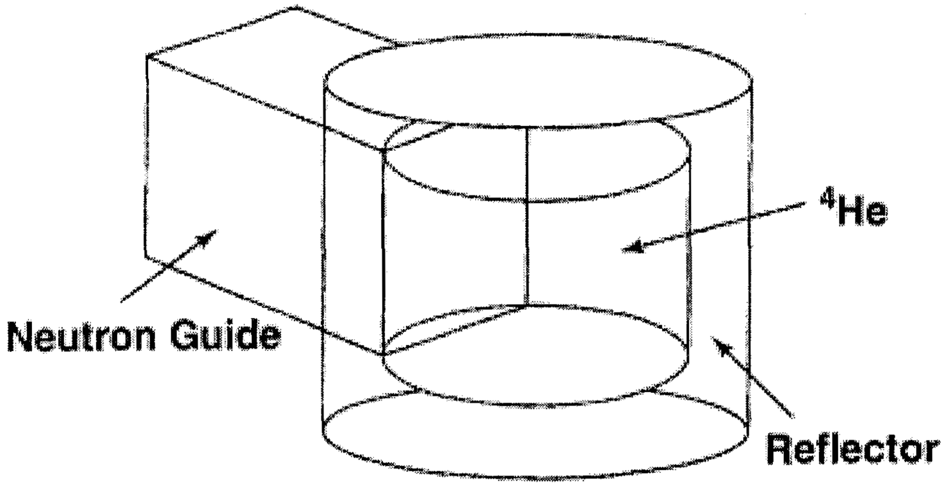

Figure 1

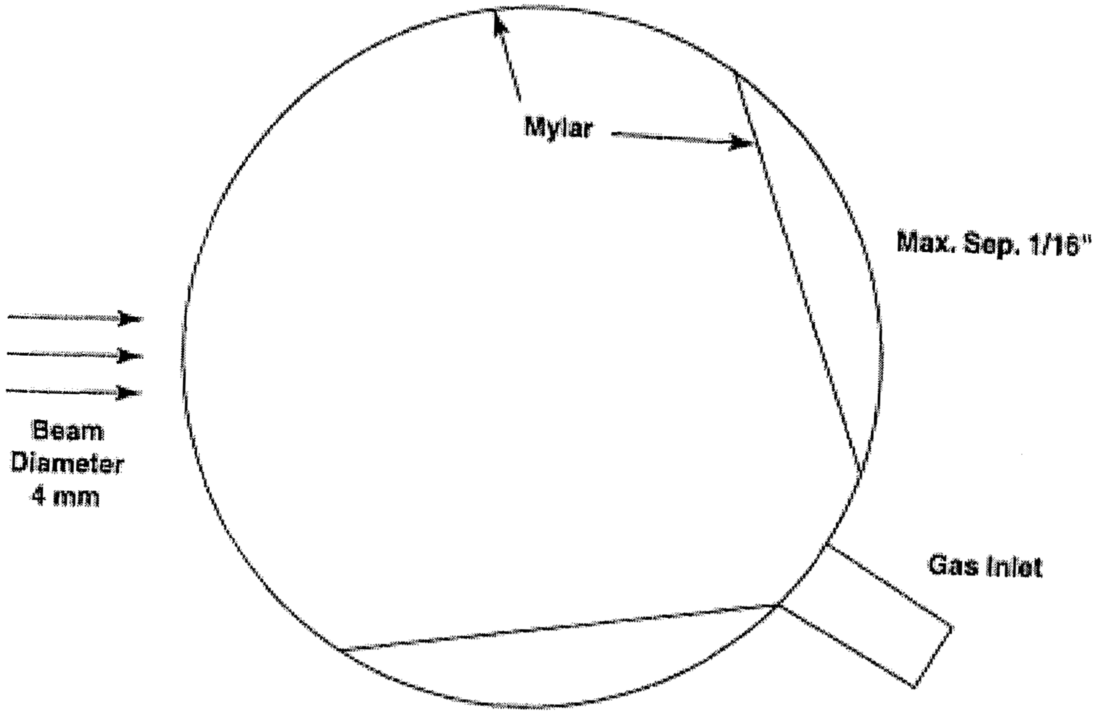

Figure 2

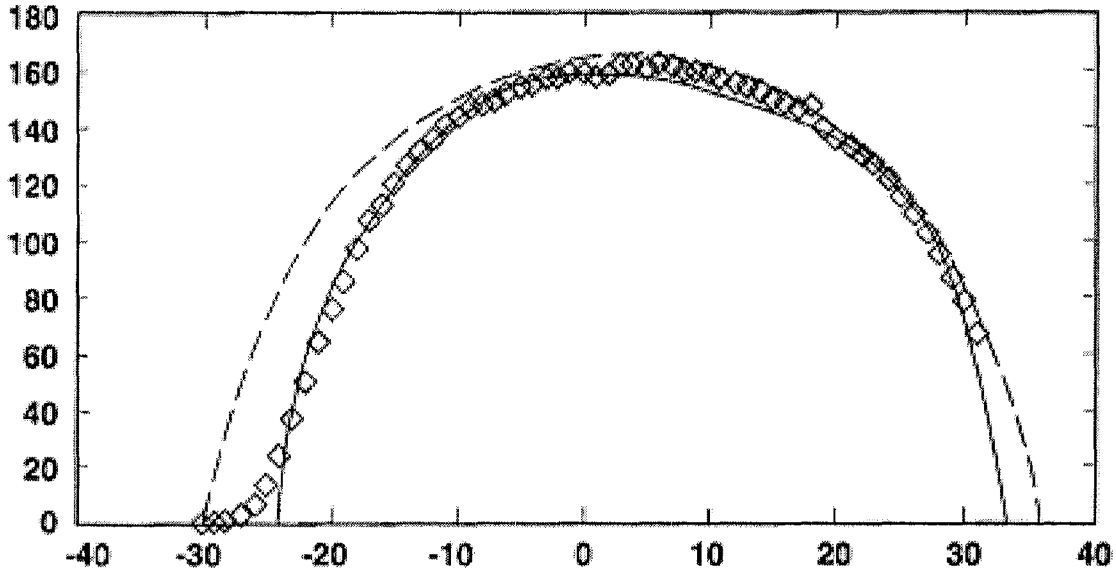

Figure 3